Burst Detector Sensitivity: Past, Present & Future

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Abstract. I compare the burst detection sensitivity of *CGRO*'s BATSE, *Swift*'s BAT, the *GLAST* Burst Monitor (GBM) and *EXIST* as a function of a burst's spectrum and duration. A detector's overall burst sensitivity depends on its energy sensitivity and set of accumulations times Δt; these two factors shape the detected burst population. For example, relative to BATSE, the BAT's softer energy band decreases the detection rate of short, hard bursts, while the BAT's longer accumulation times increase the detection rate of long, soft bursts. Consequently, *Swift* is detecting long, low fluence bursts (2-3$\times$ fainter than BATSE).

Keywords: gamma-ray bursts; detectors
PACS: 98.70.Rz, 95.55.Ka

What is the relative sensitivity of different detectors for detecting gamma-ray bursts, and how should this sensitivity be compared? How do these differences shape the observed burst populations, which must be taken into account in determining the underlying burst distribution? Here I compare BATSE's Large Area Detectors on *CGRO* (the past), the Burst Alert Telescope (BAT)[1] on *Swift* (the present), and the *GLAST* Burst Monitor (GBM) and *EXIST* (the future). BATSE and the GBM are/were sets of NaI(Tl) detectors while the BAT and *EXIST* are/will be CZT coded mask detectors. The energy range of NaI(Tl) detectors is ~20–1000 keV while for CZT it is ~10–150 keV. I apply a semi-analytic methodology using simplified models of the trigger systems of the different detectors.

Most instruments detect bursts using either rate triggers or image triggers. A rate trigger determines whether the increase in the number of counts in a time bin Δt and energy band ΔE over the expected number of background counts is statistically significant. An image trigger determines whether the image formed from the counts in the time bin Δt and energy band ΔE contains a new point source. Usually an image trigger is preceded by a rate trigger that starts the imaging process[2]; the rate trigger is set to permit many false positives that are eliminated by the image trigger. If the number of burst counts is S and the number of non-burst counts is B, then the rate trigger significance σ_r (for BATSE and the GBM) and the image trigger significance σ_i for Δt and ΔE are

$$\sigma_r = \frac{S}{\sqrt{B}} \qquad \text{and} \qquad \sigma_i = \frac{f_c S}{\sqrt{B+S}} \tag{1}$$

where f_c accounts for the finite size of the detector pixels. For *Swift* f_c ~0.7[3], which explains why for a given burst the rate trigger significance is greater than the imaging significance[4]. The BAT uses a more complex rate trigger than shown above. For

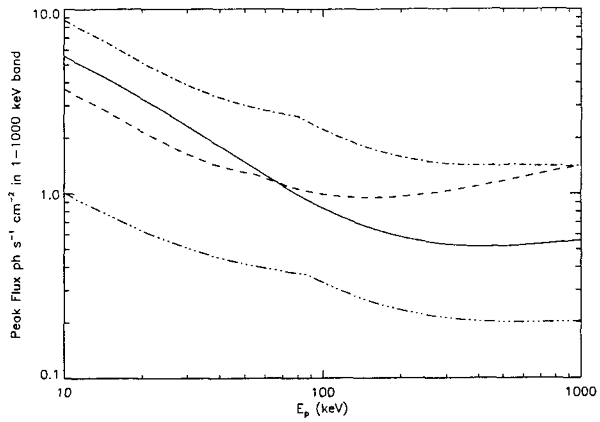

FIGURE 1. Threshold value of F_T (1–1000 keV peak flux) as a function of E_p for BATSE (solid), the BAT (dashed), the GBM (dot-dashed) and one *EXIST* telescope (3 dots-dashed). The spectrum has a low energy spectral index of α= -0.5 and a high energy index of β= -2.

directions other than the burst position the counts S from the burst contribute to the average flux level, and therefore in imaging S is compared to $\sqrt{B+S}$. A trigger occurs when σ_r or σ_i exceeds a threshold value that is sufficiently high for a small probability of false positives. Because of the similarity of σ_r and σ_i, particularly since usually $B \gg S$ near threshold, the methodologies for evaluating the sensitivity of rate and image triggers are essentially the same[5].

Whether a given detector and its trigger system detects a burst depends on the number of counts S the burst produces in time bin Δt and energy band ΔE. If bursts differed only in their intensity, we could use a common measure of burst intensity, but bursts differ in their temporal and spectral properties, and thus a given detector is more sensitive to some burst types and less to others. While it is impossible to characterize a burst completely by only a few parameters, approximate burst types can be described by a few parameters. For burst detection, I characterize bursts by: E_p—the energy at the peak of $E^2N(E) \propto \nu f_\nu$ for the spectrum averaged over Δt; and T_{90}—the time duration for 90% of the flux. I characterize the burst intensity by the peak flux F_T over 1 s in the 1–1000 keV band. A detector does not measure F_T directly; since a spectral fit is necessary to convert from counts to flux, F_T need not be over ΔE[5].

I first evaluate the sensitivity of the four detectors to E_p, disregarding the burst duration. Thus I assume that bursts have constant emission over Δt=1 s. Then S is proportional to the burst spectrum times the detector efficiency integrated over ΔE. BATSE used only one value of ΔE at any given time, typically ΔE=50–300 keV, but later detectors use a set of ΔE simultaneously. Figure 1 shows the threshold F_T as a function of E_p for BATSE, BAT, GBM and *EXIST*. While I characterize the spectrum primarily by E_p, there remains a dependence on the high and low energy spectral indices, β and α (not shown by Figure 1). In all cases I use the maximum sensitivity over the FOV. The scalloping results from multiple values of ΔE.

As a CZT detector, the BAT's sensitivity is shifted to lower energy than BATSE's. The

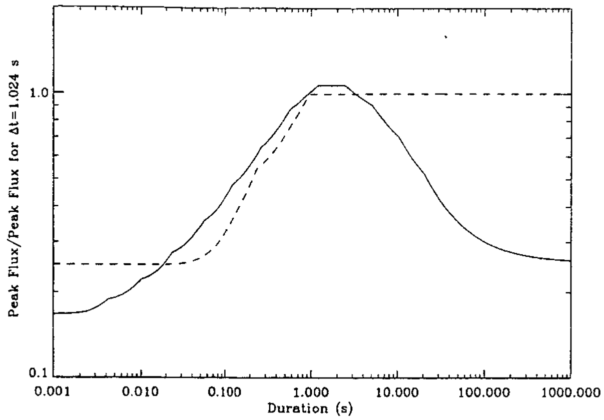

FIGURE 2. The ratio of the detector sensitivity for a trigger system using a set of Δt values to the rate trigger sensitivity for Δt=1.024 s alone; ratios less than 1 indicate an increase in sensitivity resulting from additional values of Δt. The dashed curve is for BATSE's set of Δt, while the dashed curve is for the BAT.

GBM's detectors will be smaller than BATSE's, while *EXIST* will have larger detectors than the BAT. Note that these sensitivity curves are all for Δt=1 s; increasing Δt increases the BAT's sensitivity to long bursts.

As Δt increases, the number of burst counts S may increase but the number of background counts B definitely increases. Thus there is a competition between changes in S and B as Δt changes. The affect on the sensitivity of increasing or decreasing Δt depends on the burst lightcurve; the duration T_{90} is a key parameter characterizing the lightcurve. If $T_{90} \ll \Delta t$ then the dilution of the burst counts by the background can be decreased by decreasing Δt, but if $T_{90} \gg \Delta t$ then increasing Δt might increase the number of burst counts relative to the background. Detectors use more than one Δt; the overall sensitivity is the lowest value of F_T for any Δt. Figure 2 shows as a function of T_{90} the ratio of the detector sensitivity for a set of Δt to the rate trigger sensitivity for Δt=1.024 s alone; ratios less than 1 indicate an increase in sensitivity resulting from the additional values of Δt and the trigger type. The burst is assumed to have an exponential lightcurve. BATSE (dashed curve) used a simple rate trigger with Δt=0.064, 0.256 and 1.024 s. Thus, for $T_{90} > 1.024$ s the Δt=1.024 s trigger dominates, and the ratio equals 1, while for $T_{90} < 1.024$ s the smaller Δt values increase the sensitivity (smaller ratios) to short duration bursts. The BAT, GBM and *EXIST* (will) use both smaller and longer Δt values than BATSE did. The solid curve on Figure 2 was calculated for the BAT's image trigger; note the increase in sensitivity over BATSE's set of Δt for both long and short bursts. The increase in sensitivity to short duration bursts is not as dramatic as for long duration bursts because σ_i does not decrease indefinitely as B decreases for fixed S (see eq. 1). The reduced sensitivity of an image trigger relative to a simple rate trigger for very short bursts does NOT mean that a rate trigger is superior to an image trigger: an image trigger localizes the burst, and does not require a model of the background rate.

The spectral and temporal dependencies of the burst sensitivity can be combined to produce the threshold F_T as a function of both E_p and T_{90}. Figure 3 presents the ratio

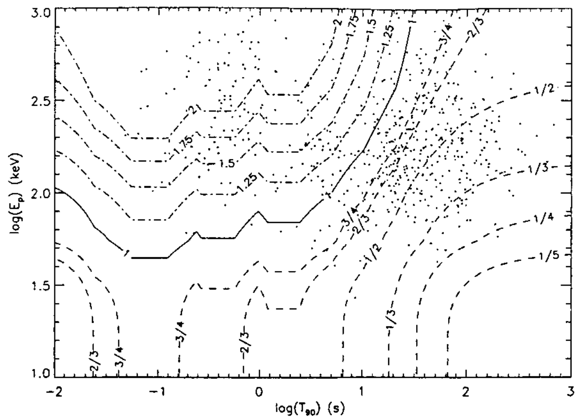

FIGURE 3. Contour plot of the ratio of the sensitivities of the BAT and BATSE as a function of E_p and T_{90}; a ratio less than one indicates that the BAT is more sensitive than BATSE. α=-0.5 and β=-2 are assumed. Also plotted are the E_p and T_{90} for a set of BATSE bursts with enough counts for spectral fits.

of the sensitivities of the BAT and BATSE; a ratio less than one indicates that the BAT is more sensitive than BATSE at that particular set of E_p and T_{90}. Also plotted are the E_p and T_{90} for a set of BATSE bursts. As can be seen, the short, hard bursts are in a region of parameter space where the BAT is less sensitive than BATSE while the BAT is more sensitive to long, soft bursts. The contours' gradient shows that the BAT detects fewer short, hard burst because its energy band is lower than BATSE's was, and the BAT detects more long, soft bursts both because of its lower energy band and its greater sensitivity to long bursts. This explains the shift in the duration distributions. Because the BAT is significantly more sensitive to long bursts, the average fluence detected by the BAT is ~ 2.5 times fainter than BATSE's. As a burst's redshift is increased, its duration is dilated and its spectrum is redshifted. Thus high redshift bursts are shifted towards the parameter space region where *Swift* is particularly sensitive. Note that *Beppo-SAX* and *HETE-II* use(d) imaging triggers with low energy detectors, explaining why these two detectors detect(ed) few short bursts and many X-ray rich bursts and X-ray Flashes.

ACKNOWLEDGMENTS

I thank members of the BAT instrument team for informative discussions; conclusions regarding the BAT's sensitivity are mine, and do not represent the BAT team.

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